Higgs-Radion Mixing in the RS and LHC Higgs-like Excesses

Jack Gunion
U.C. Davis

Grenoble Higgs Workshop, February 2, 2012

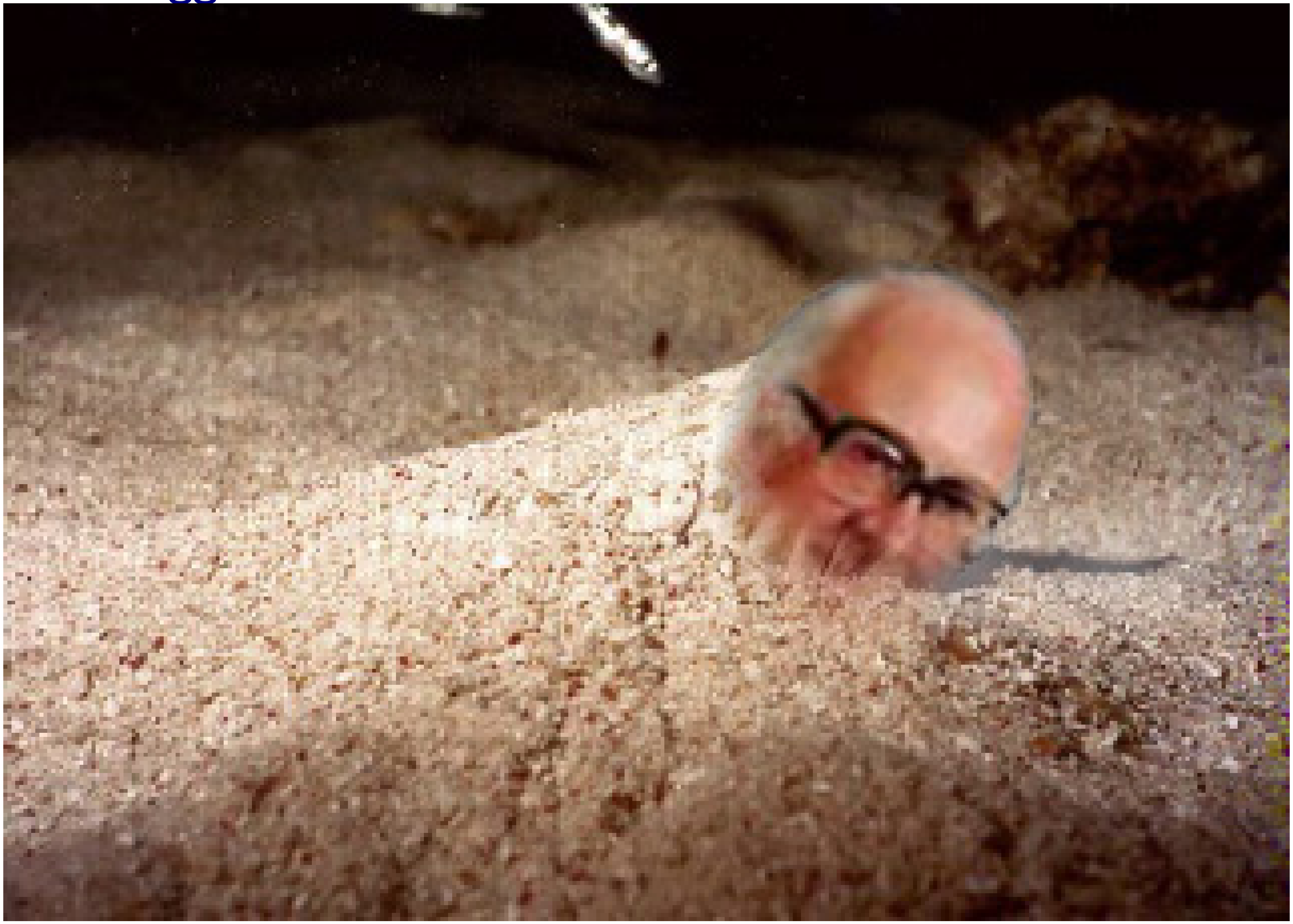
with B. Grzadkowski

Higgs-like LHC Excesses

Is what we are seeing a Higgs-like chameleon?

Higgs-like LHC Excesses

Or is it THE Higgs?



- **Given that the mass(es) is(are) of order $125\ \mathrm{GeV}$, the MSSM or the much more attractive NMSSM extension thereof is a natural candidate theory.**

  After all, SUSY solves the hierarchy problem, predicts gauge coupling unification at the GUT scale and so forth.

  However:

  - **A SM-like Higgs with mass as large as $125\ \mathrm{GeV}$ is a bit of a stretch. Even in the NMSSM $125\ \mathrm{GeV}$ is "on the edge" for semi-universal (NUHM) GUT boundary conditions (and not possible for full CNMSSM b.c.).**
  - **This is aggravated if the signal is $>$ SM.**
  - **And, even more problematically, there may be more than one 'excess' in the data (cf. CMS data).**

- **The only other really attractive alternate solution to the hierarchy problem that provides a self-contained ultraviolet complete framework is to allow extra dimensions.**

  One particular implementation is the Randall Sundrum model in which there is a warped 5th dimension.

The Randall Sundrum Model

- The background RS metric that solves Einstein's equations takes the form[1]

$$ds^2 = e^{-2m_0 b_0 |y|}\eta_{\mu\nu}dx^\mu dx^\nu - b_0^2 dy^2 \tag{1}$$

where y is the coordinate for the 5th dimension with $|y| \leq 1/2$.

- The graviton and radion fields, $h_{\mu\nu}(x,y)$ and $\phi_0(x)$, are the quantum fluctuations relative to the background metric $\eta_{\mu\nu}$ and b_0, respectively.

- In the simplest case, only gravity propagates in the bulk while the SM is located on the infrared (or TeV) brane at $y = 1/2$ and

$$\mathcal{L}_{\rm int} = -\frac{1}{\widehat{\Lambda}_W}\sum_{n\neq 0} h^n_{\mu\nu}T^{\mu\nu} - \frac{\phi_0}{\Lambda_\phi}T^\mu_\mu \tag{2}$$

where $h^n_{\mu\nu}(x)$ are the Kaluza-Klein (KK) modes (with mass m_n) of the graviton field $h_{\mu\nu}(x,y)$.

- The parameters:

  $\widehat{\Lambda}_W \simeq \sqrt{2} m_{Pl} \Omega_0$, where $\Omega_0 = e^{-\frac{1}{2} m_0 b_0}$, and $\Lambda_\phi = \sqrt{3}\,\widehat{\Lambda}_W$.

- If matter propagates in the bulk then the interactions of gravitons and radion with matter are controlled by the overlap of appropriate extra-dimensional profiles and corrections to (2) appear.

- In addition to the radion, the model contains a conventional Higgs boson, h_0.

- The RS model provides a simple solution to the hierarchy problem if the Higgs is placed on the TeV brane at $y = 1/2$ by virtue of the fact that the 4D electro-weak scale v_0 is given in terms of the $\mathcal{O}(m_{Pl})$ 5D Higgs vev, $\widehat{v}$, by:

$$v_0 = \Omega_0 \widehat{v} = e^{-\frac{1}{2} m_0 b_0} \widehat{v} \sim 1 \text{ TeV} \quad \text{for} \quad \frac{1}{2} m_0 b_0 \sim 35\,. \tag{3}$$

To solve the hierarchy problem, $\Lambda_\phi = \sqrt{6} m_{Pl} \Omega_0 \lesssim 1 - 10~\mathrm{TeV}$ needed.

- m_0/m_{Pl} is a particularly crucial parameter that characterizes the 5-dimensional curvature.

  $m_0/m_{Pl} \gtrsim 0.5$ is favored for fitting the LHC Higgs excesses and by bounds on FCNC and PEW constraints.

  Views on m_0/m_{Pl} are changing:

  – Original: $R_5/M_5^2 < 1$ (M_5 being the 5D Planck scale and $R_5 = 20m_0^2$ the size of the 5D curvature) is needed to suppress higher curvature terms in the 5D action: $\Rightarrow m_0/m_{Pl} \lesssim 0.15$.

  – New: [9] argues that R_5/Λ^2 ($\Lambda =$ energy scale at which the 5D gravity theory becomes strongly coupled, with NDA estimate of $\Lambda \sim 2\sqrt{3}\pi M_5$), is the appropriate measure,
  $\Rightarrow m_0/m_{Pl} < \sqrt{3\pi^3/(5\sqrt{5})} \sim 3$ acceptable.

- Note: the mass of 1st KK graviton excitation (G^1) is related to m_0/m_{Pl}

and Λ_ϕ by

$$m_1^{\rm KK} = \frac{(m_0/m_{Pl}) x_1^{\rm KK}}{\sqrt{6}} \Lambda_\phi \,, \tag{4}$$

where $x_1^{\rm KK} \sim 3.83$.

$\Rightarrow$ large m_0/m_{Pl} if the lower bound on $m_1^{\rm KK}$ is large and $\Lambda_\phi \sim 1~{\rm TeV}$.

- In the simplest RS scenario, the SM fermions and gauge bosons are confined to the brane.

  Now regarded as highly problematical:

  – Higher-dimensional operators in the 5D effective field theory are suppressed only by ${\rm TeV}^{-1}$, $\Rightarrow$ FCNC processes and PEW observable corrections are predicted to be much too large.
  $\Rightarrow$ no explanation of the flavor hierarchies.

- Must move fermions and gauge bosons (but not Higgs) off the brane [2][3][4][5][6][7][8][9]

The SM particles = zero-modes of the 5D fields and the profile of a SM fermion in the extra dimension can be adjusted using a mass parameter.

Two possibilities:

1. **If 1st and 2nd generation fermion profiles peak near the Planck brane then FCNC operators and PEW corrections will be suppressed by scales** $\gg \text{TeV}$**.**
   Even with this arrangement it is estimated that the g^1**,** W^1 **and** Z^1 **masses must be larger than about** $3\ \text{TeV}$ **(see the summary in [9]).**
2. **Use fairly flat profiles for the 1st and 2nd generation fermions in the 5th dimension.**
   $\Rightarrow$ **the coupling of light quarks to** g^1, W^1, Z^1**, proportional to the integral of the square of the fermion profile multiplied by the gauge boson profile, will be very small, implying small FCNC.**
   PEW constraints would still be very problematical unless a special 5D GIM mechanism is employed [11].

In either case, the interactions of Eq. (2) are greatly modified when gauge bosons and fermions are allowed to propagate in the bulk,

- If the gauge bosons and fermions do not propagate in the bulk, then the strongest limits on Λ_ϕ come, via Eq. (4), from the lower bound placed by the LHC on the first graviton KK excitation (see, for example, [13] and [14] for the ATLAS and CMS limits).

- However, when the fermions propagate in the bulk, the couplings of light fermion pairs to G^1 are greatly reduced and these limits do not apply.

- When gauge bosons propagate in the bulk, a potentially important experimental limit on the model comes from lower bounds on the 1st excitation of the gluon, g^1.

  In the model of [12], in which light fermion profiles peak near the Planck brane, there is a universal component to the light quark coupling $q\bar{q}g^1$ that is roughly equal to the SM coupling g times a factor of ζ^{-1}, where $\zeta \sim \sqrt{\frac{1}{2}m_0 b_0} \sim 5-6$.

  The suppression is due to the fact that the light quarks are localized near the Planck brane whereas the KK gluon is localized near the TeV brane.

Even with such suppression, the LHC g^1 production rate due to $u\bar{u}$ and $d\bar{d}$ collisions is large.

Further, the $t_R\bar{t}_R g^1$ coupling is large since the t_R profile peaks near the TeV brane – the prediction of [12] is $g_{t_R\bar{t}_R g^1} \sim \zeta g$.

$\Rightarrow g^1 \to t\bar{t}$ decays dominant.

$\Rightarrow$ lower bound of $m_1^g \gtrsim 1.5~\mathrm{TeV}$ [15] using an update of the analysis of [12]. ([16] gives a weaker bound of $m_1^g > 0.84~\mathrm{TeV}$.) .

- In terms of Λ_ϕ, we have the following relations:

$$\frac{m_0}{m_{Pl}} = \frac{\sqrt{6}}{x_1^g}\frac{m_1^g}{\Lambda_\phi} \simeq \frac{m_1^g}{\Lambda_\phi}, \quad \text{and} \quad \frac{1}{2}m_0 b_0 = -\log\left(\frac{\Lambda_\phi}{\sqrt{6}m_{Pl}}\right) \tag{5}$$

where $x_1^g = 2.45$ is the 1st zero of an appropriate Bessel function.

If the model really solves the hierarchy problem then $\widehat{\Lambda}_W$ in Eq. (2) cannot be much larger than $1~\mathrm{TeV}$. Let us take $\widehat{\Lambda}_W \lesssim 5.5~\mathrm{TeV}$ as an extreme possibility, which implies $\Lambda_\phi = \sqrt{3}\widehat{\Lambda}_W \lesssim 10~\mathrm{TeV}$.

If we adopt the CMS limit of $m_1^g > 1.5~\mathrm{TeV}$ then (5) implies a lower limit on the 5-dimensional curvature of $m_0/m_{Pl} \gtrsim 0.15$.

Thus, a significant lower bound on m_1^g implies that only relatively large values for m_0/m_{Pl} are allowed. $\Rightarrow$ probably ok given latest ideas.

- Another approach:

  Take light fermion profiles to be flat in 5th dimension. $\Rightarrow$ $q\bar{q}g^1, \ldots$ couplings are small.

  $\Rightarrow$ FCNC ok and PEW ok if introduce a 5D GIM mechanism [11].

  $\Rightarrow$ no direct experimental bound on m_1^g.

  Λ_ϕ?

  if $\Lambda_\phi = 1~\mathrm{TeV}$, for $m_0/m_{Pl} = 0.01, 0.1$ Eq. (5) implies $m_1^g = 10, 100~\mathrm{GeV}$.

  Could the g^1 really have escaped discovery for such low masses?

  If there is no firm bound on m_1^g $\Rightarrow$ discuss the phenomenology for fixed Λ_ϕ. We will consider $\Lambda_\phi = 1~\mathrm{TeV}$ and $1.5~\mathrm{TeV}$.

Higgs-Radion Mixing

- **Since the radion and higgs fields have the same quantum numbers, they can mix. [17]**

$$S_\xi = \xi \int d^4x \sqrt{g_{\rm vis}} R(g_{\rm vis}) \widehat{H}^\dagger \widehat{H} \,, \tag{6}$$

The physical mass eigenstates, h and ϕ, are obtained by diagonalizing and canonically normalizing the kinetic energy terms.

The diagonalization procedures and results for the h and ϕ using our notation can be found in [10] (see also [17][18]).

In the end, one finds

$$\begin{aligned} h_0 &= dh + c\phi \quad -\phi_0 = a\phi + bh \,, \quad \text{where} \\ d &= \cos\theta - t\sin\theta,\ c = \sin\theta + t\cos\theta,\ a = -\frac{\cos\theta}{Z},\ b = \frac{\sin\theta}{Z}\,, \end{aligned} \tag{7}$$

with

$$t = 6\xi\gamma/Z, \quad Z^2 = 1 + 6\xi\gamma^2(1-6\xi), \quad \tan 2\theta = \frac{12\gamma\xi Z m_{h_0}^2}{m_{\phi_0}^2 - m_{h_0}^2[Z^2 - 36\xi^2\gamma^2]}. \tag{8}$$

Here $m_{h_0}^2$ and $m_{\phi_0}^2$ are the Higgs and radion masses before mixing.

Consistency of the diagonalization imposes strong restrictions on the possible ξ values as a function of the final eigenstate masses m_h and m_ϕ, which restrictions depend strongly on the ratio $\gamma \equiv v_0/\Lambda_\phi$ ($v_0 = 246\ \mathrm{GeV}$).

- The full Feynman rules after mixing for the h and ϕ interactions with gauge bosons and fermions located in the bulk were derived in [19].

Of particular note are the anomaly terms associated with the ϕ_0 interactions before mixing. After mixing we find

$$g_h = (d + \gamma b) \quad g_\phi = (c + \gamma a) \quad g_h^r = \gamma b \quad g_\phi^r = \gamma a \,. \tag{9}$$

$$\begin{aligned}
c_g^{h,\phi} &= -\frac{\alpha_s}{4\pi v}\left[g_{h,\phi}\sum_i F_{1/2}(\tau_i) - 2(b_3 + \frac{2\pi}{\alpha_s \frac{1}{2} m_0 b_0}) g_{h,\phi}^r\right] \\
c_\gamma^{h,\phi} &= -\frac{\alpha}{2\pi v}\left[g_{h,\phi}\sum_i e_i^2 N_c^i F_i(\tau_i) - (b_2 + b_Y + \frac{2\pi}{\alpha \frac{1}{2} m_0 b_0}) g_{h,\phi}^r\right]
\end{aligned} \tag{10}$$

New relative to old on-the-brane results are the $2\pi\ldots$ correctons to the g^r terms. They can be significant when m_0/m_{Pl} is small.

- There are also modifications to the WW and ZZ couplings of the h and ϕ relative to old on-the-brane results.

  Without bulk propagation, these couplings were simply given by SM couplings (proportional to the metric tensor $\eta^{\mu\nu}$) times g_h or g_ϕ.

  For the bulk propagation case, there are additional terms in the interaction Lagrangian that lead to Feynman rules that have terms not proportional to $\eta^{\mu\nu}$, see [19].

  For example, for the W we have (before mixing)

$$\mathcal{L} \ni h_0 \frac{2m_W^2}{v} W_\mu^\dagger W^\mu - \phi_0 \frac{2m_W^2}{\Lambda_\phi} \left[W_\mu^\dagger W^\mu (1-\kappa_W) + W_{\mu\nu}^\dagger W^{\mu\nu} \frac{1}{4m_W^2(\frac{1}{2}m_0 b_0)} \right] \tag{11}$$

After mixing, this becomes, for example for the h interaction

$$\mathcal{L} \ni \equiv h \frac{2m_W^2}{v} g_h^W \left[W_\mu^\dagger W^\mu + \eta_h^W W_{\mu\nu}^\dagger W^{\mu\nu} \right] \tag{12}$$

with a similar result for the ϕ.

Here,

$$g_{h,\phi}^V \equiv g_{h,\phi} - g_{h,\phi}^r \kappa_V \,, \quad \eta_{h,\phi}^V \equiv \frac{g_{h,\phi}^r}{g_{h,\phi}^V} \frac{1}{4m_V^2(\frac{1}{2}m_0 b_0)} \,. \tag{13}$$

Net Feynman rule for the hWW:

$$i g m_W g_h^W \left[\eta_{\mu\nu}(1 - 2k^+ \cdot k^- \eta_h^W) + 2\eta_h^W k_\mu^+ k_\nu^- \right] \tag{14}$$

where k^+, k^- are the momenta of the W^+, W^-, respectively.

- For the fermions, we assume profiles such that there are no corrections to the h_0 and ϕ_0 couplings due to propagation in the bulk.

  This is a very good approximation for the top quark quark which must be localized near the TeV brane.

Also for the bottom quark the approximation is better than 20%, see [19].

Even though the approximation is not necessarily good for light quarks, it is only the heavy quarks that impact the phenomenology of the higgs-radion system.

LHC Excesses

- **In the context of the higgs-radion model, positive signals can only arise for two masses.**
- **If more than two excesses were to ultimately emerge, then a more complicated Higgs sector will be required than the single h_0 case we study here.**

  Certainly, one can consider including extra Higgs singlets or doublets.

  For the moment, we presume that there are at most two excesses. In this case, it is sufficient to pursue the single Higgs plus radion model.

We will consider a few cases. Errors quoted for the excesses are $\pm 1\sigma$.

1. **ATLAS:**

   $125~\mathrm{GeV}$: $\gamma\gamma$ excess of $2^{+0.8}_{-0.8}\times$SM

   $125~\mathrm{GeV}$: 4ℓ excess of $1.5^{+1.5}_{-1}\times$ SM

2. **CMSA:**

   $124~\mathrm{GeV}$: $\gamma\gamma$ excess of $1.7^{+0.8}_{-0.7}\times$ SM

   $124~\mathrm{GeV}$: 4ℓ excess of $0.5^{+1.1}_{-0.7}\times$SM

   $120~\mathrm{GeV}$: 4ℓ excess of $\sim 2^{+1.5}_{-1}\times$SM but $\gamma\gamma$ rate $< 0.5\times$SM.

3. **CMSB:**

   $124~\mathrm{GeV}$: as above

   $137~\mathrm{GeV}$: $\gamma\gamma$ excess of $1.5^{+0.8}_{-0.8}\times$SM

   $137~\mathrm{GeV}$: $4\ell < 0.2\times$SM

Notes:

- For plots use $125~\mathrm{GeV}$ always: no change if $125~\mathrm{GeV} \to 124~\mathrm{GeV}$.
- As discussed, consider two different kinds models:

1. lower bound on m_1^g of $1.5~\mathrm{TeV}$
2. fixed Λ_ϕ

Lower bound of $m_1^g = 1.5\ \mathrm{TeV}$

- Recall that Λ_ϕ will be correlated with m_0/m_{Pl}.

$$\frac{m_0}{m_{Pl}} \simeq \frac{m_1^g}{\Lambda_\phi} \tag{15}$$

$\Rightarrow$

For small m_0/m_{Pl}, Λ_ϕ is too large, so only solve hierarchy if m_0/m_{Pl} is $\gtrsim 0.2$.

- Only have time for a limited selection of situations.

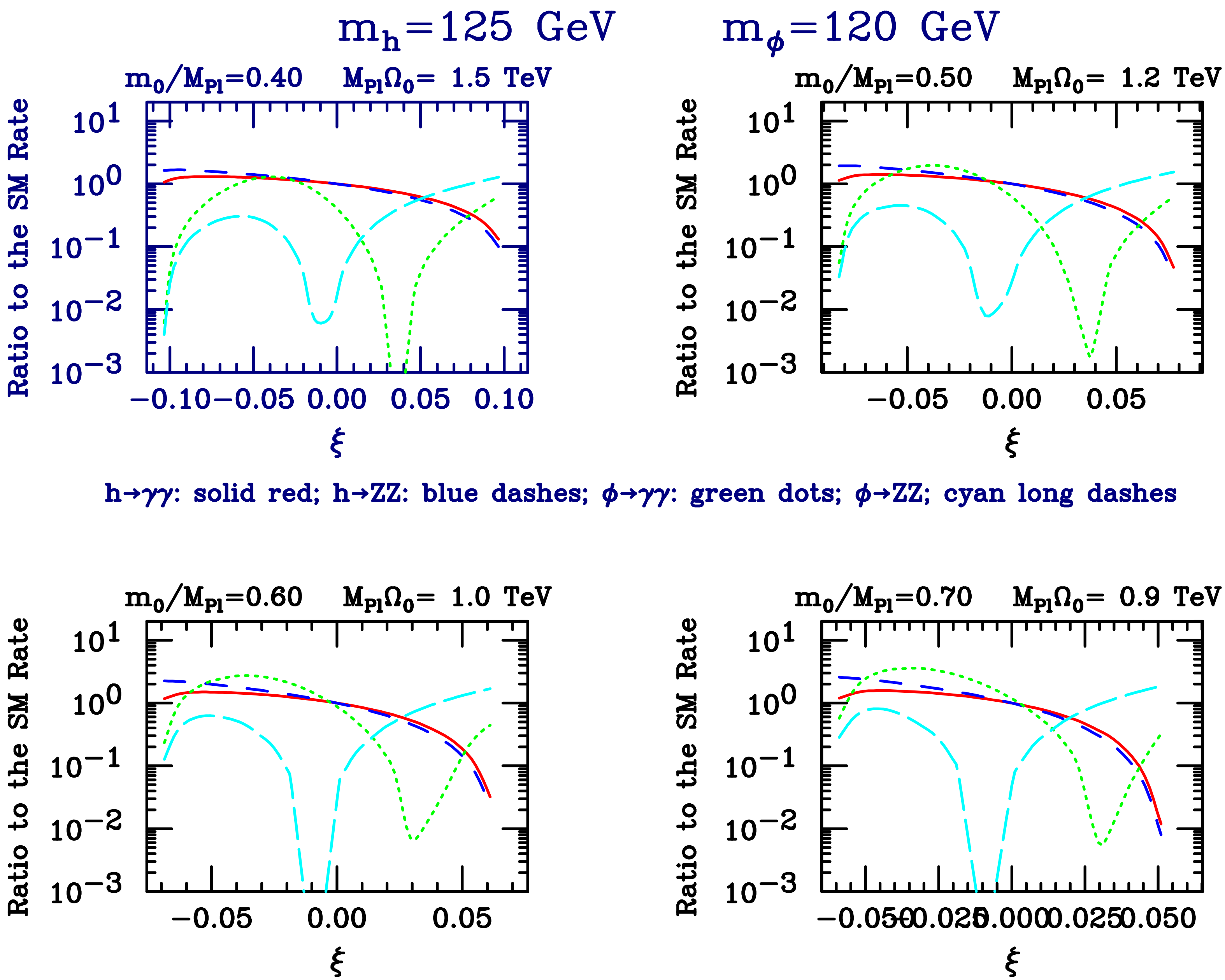


Figure 1: We plot $\gamma\gamma$ and ZZ relative to SM vs ξ.

Only 125 GeV excess

- If want no excesses at ~ 120 GeV, but $\gamma\gamma$ excess at 125 GeV of order $\gtrsim 1.5\times$SM, then $m_0/m_{Pl} = 0.4$ and $\xi \sim -0.09$ are good choices.

  4ℓ signal at 125 GeV is $> \gamma\gamma$ but still within error.

- For the reversed assignments of $m_h = 120$ GeV and $m_\phi = 125$ GeV, no decent description of the ATLAS 125 GeV excesses with signals at 120 GeV being sufficiently suppressed.

Excesses at 125 GeV and 120 GeV

- Higgs-radion scenario fails.

  In the regions of ξ for which appropriate signals are present at 125 GeV from the h, the 4ℓ and $\gamma\gamma$ rates at 120 GeV are either both suppressed or it is the $\gamma\gamma$ rate that is enhanced more than the 4ℓ rate at 120 GeV. This phenomenon persists at higher m_0/m_{Pl} values.

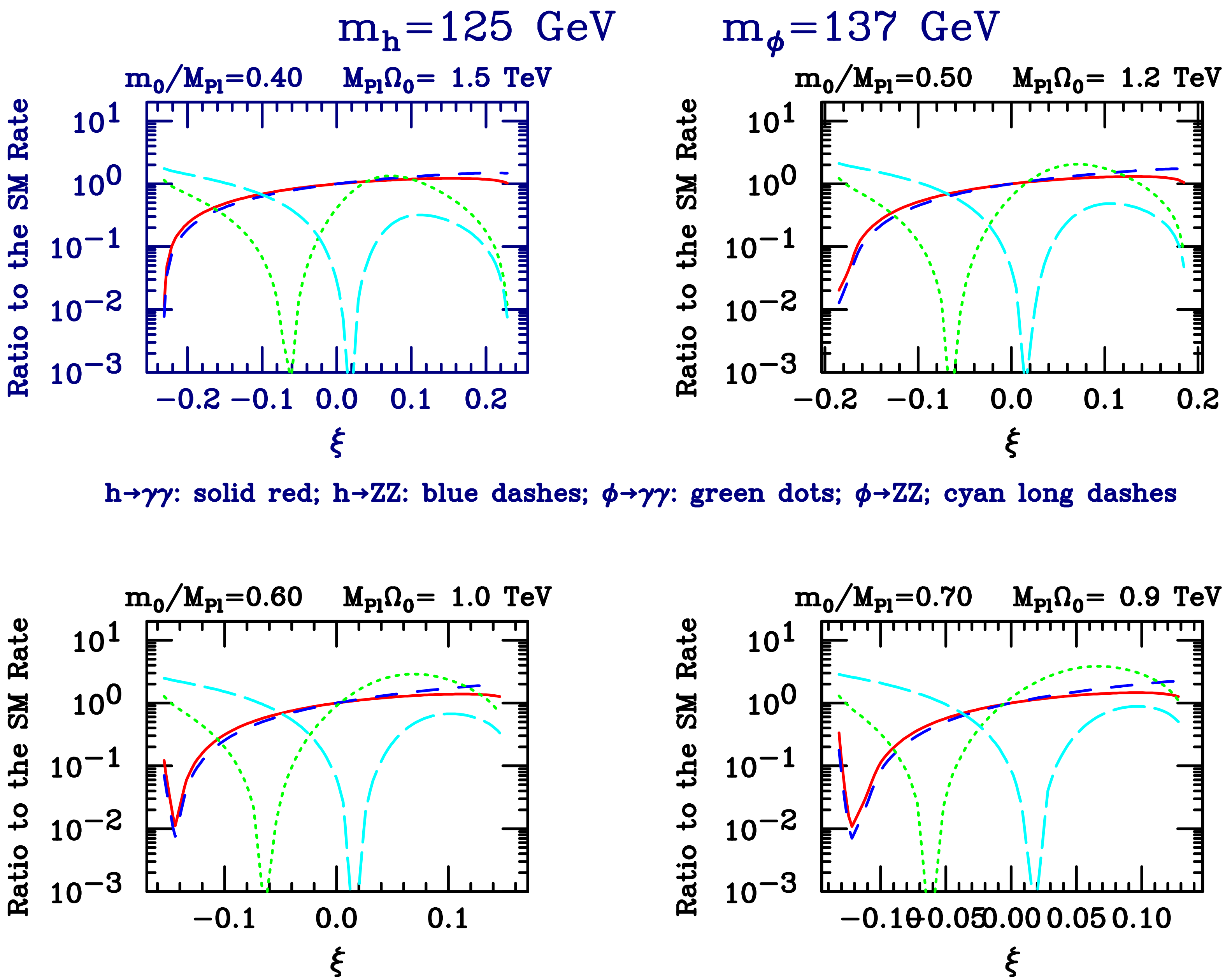


Figure 2: $\gamma\gamma$ and ZZ relative to SM vs ξ.

Signals at $\mathbf{125}$ GeV and $\mathbf{137}$ GeV

- **In Fig. 2 (previous page): $m_0/m_{Pl} = 0.5$ and $\xi = 0 \Rightarrow$**

  125 GeV: $\gamma\gamma \sim 1\times$SM and $4\ell \sim 1\times$SM

  137 GeV: $\gamma\gamma \sim 1\times$SM and 4ℓ very small

  These rates are consistent within 1σ with the CMS observations.

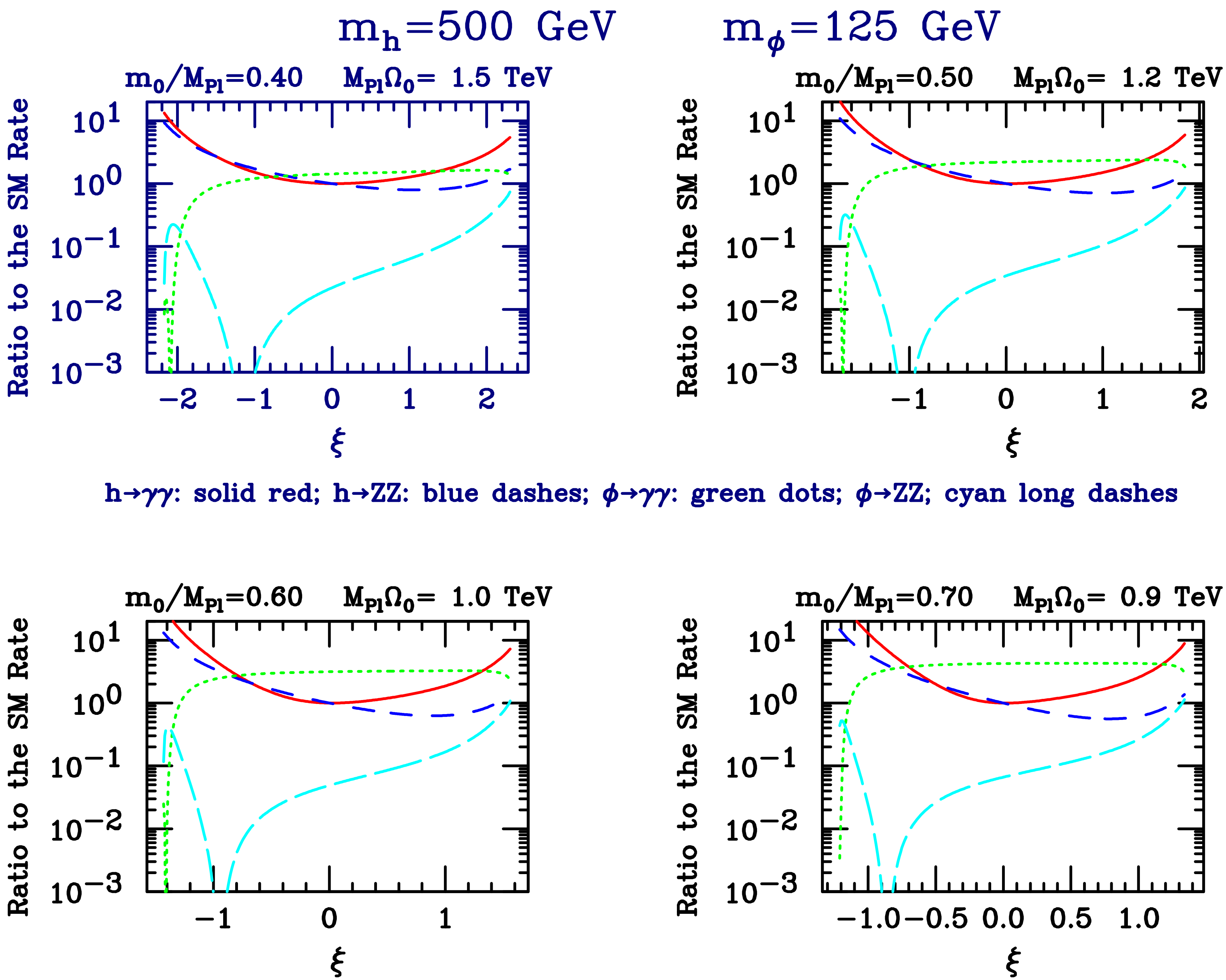


Figure 3: We plot $\gamma\gamma$ and ZZ relative to SM vs ξ.

Signals at 125 GeV and 500 GeV

- There are two choices, $m_h = 125$ GeV with $m_\phi = 500$ GeV or reverse. Let us discuss the reverse. Fig. 3.

- Large $\xi > 0 \Rightarrow \gamma\gamma \sim 2\times$SM $\gamma\gamma$ signal and $4\ell \sim 1\times$SM signal at $m_\phi = 125$ GeV for $m_0/m_{Pl} = 0.4$ and 0.5.

- $h \to 4\ell$ signal at 500 GeV $\sim$SM.

- $\gamma\gamma$ signal at 500 GeV enhanced, but SM rate small, and thus almost surely unobservable.

- 4ℓ rates at 500 GeV? ATLAS and CMS disagree.

  Probably, the heavy h in this scenario would have to be placed beyond LHC reach (for which the $m_\phi = 125$ GeV signals shown would be unchanged).

Fixed Λ_ϕ

- If fermionic profiles are quite flat, couplings of light quarks to the gauge excitations are very small. $\Rightarrow$ no bounds on m_1^g or Λ_ϕ.

  We choose to examine the phenomenology for (low) values of $\Lambda_\phi = 1$ TeV and $\Lambda_\phi = 1.5$ TeV.

- When fermions and, in particular, gauge bosons propagate in the bulk the phenomenology does not depend on Λ_ϕ alone — at fixed Λ_ϕ there is strong dependence on m_0/m_{Pl} when m_0/m_{Pl} is small.

- Only for large $m_0/m_{Pl} \gtrsim 0.5$ is the phenomenology determined almost entirely by Λ_ϕ.

  But, not the same as when all fields are on the TeV brane.

- Once again, we step through the various possible mass locations for the

Higgs and radion that are motivated by the LHC excesses in the $\gamma\gamma$ and/or 4ℓ channels.

Single resonance at 125 GeV

- The choice of $\Lambda_\phi = 1$ TeV with $m_\phi = 125$ GeV and $m_h = 120$ GeV gives a reasonable description of the ATLAS excesses at 125 GeV with no visible signals at 120 GeV in either the $\gamma\gamma$ or 4ℓ channels. (figure not shown)

  A good choice of parameters is $m_0/m_{Pl} = 1$ and $\xi = -0.015$.

- In contrast, for $\Lambda_\phi = 1.5$ TeV the 125 GeV predicted $\gamma\gamma$ and 4ℓ excesses are below $1\times$SM and thus would not provide a good description of the ATLAS excesses.

- For the reversed assignments of $m_h = 125$ GeV and $m_\phi = 120$ GeV, any choice of parameters that gives a good description of the 125 GeV signals always yields a highly observable 120 GeV signal, not appropriate for ATLAS, see next figure.

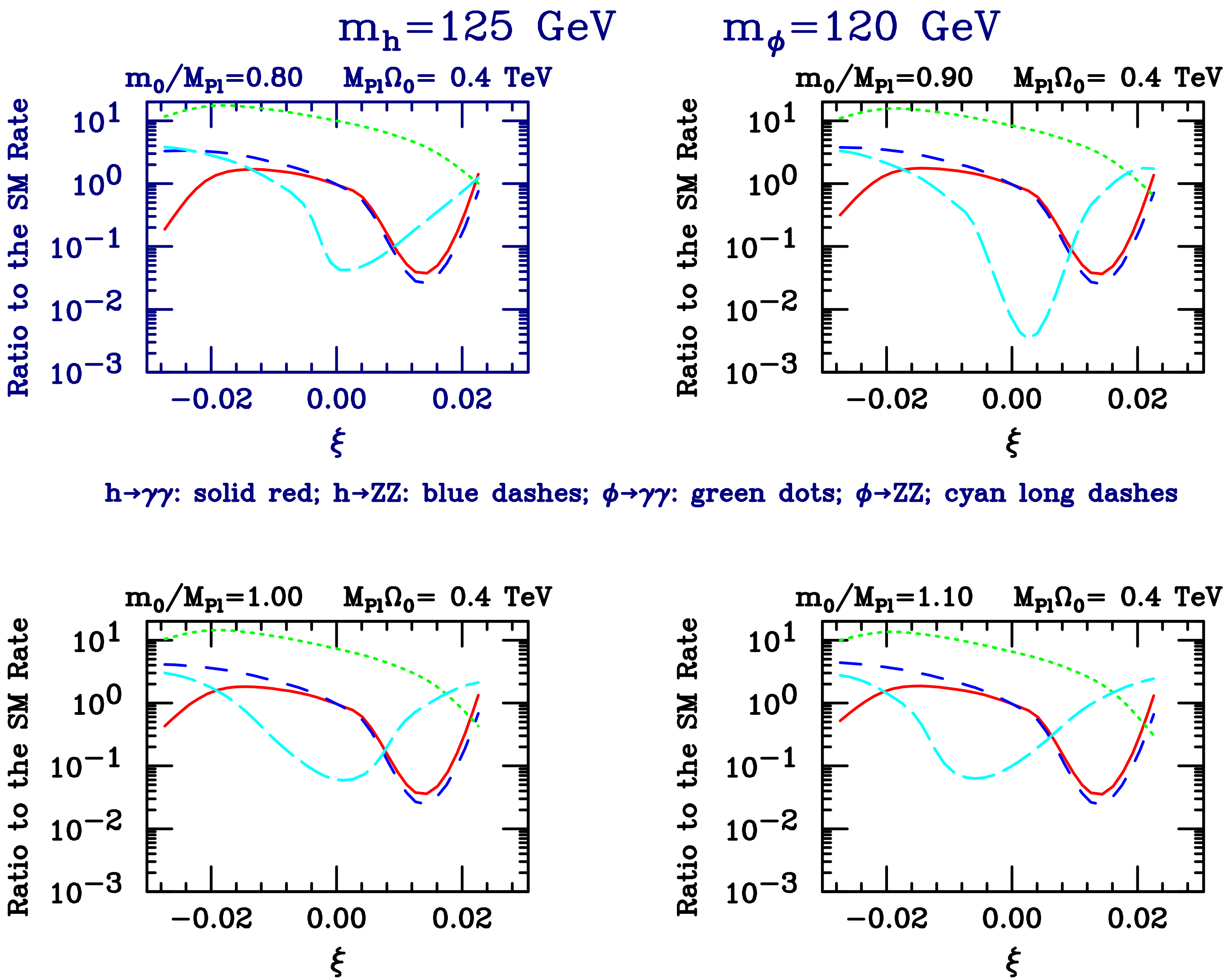


Figure 4: We plot $\gamma\gamma$ and ZZ relative to SM vs ξ taking Λ_ϕ fixed at 1 TeV.

Signals at 125 GeV and 120 GeV

- **For CMS we want:**

  125 GeV: $\gamma\gamma \sim 1.7\times$SM and $4\ell < 1.6\times$SM.

  and

  120 GeV: $4\ell \sim 2\times$SM and $\gamma\gamma < 0.4\times$SM.

  Fig. 4: for $m_h = 125$ GeV, $m_\phi = 137$ GeV, $\xi = max$ and $m_0/m_{Pl} = 1.1$ $\Rightarrow$

  125 GeV: $\gamma\gamma \sim 1.3\times$SM and $4\ell \sim 0.8\times$SM, i.e. within -1σ

  120 GeV: $4\ell \sim 2\times$SM and $\gamma\gamma \sim 0.3\times$SM, so ok.

- **With the reversed assignments of $m_h = 120$ GeV and $m_\phi = 125$ GeV a satisfactory description of the two CMS excesses is not possible.**

Signals at 125 GeV and 137 GeV

- **CMS data want:**

  125 GeV: $\gamma\gamma \sim 1.7\times$SM and $4\ell < 1.6\times$SM.

  137 GeV: $\gamma\gamma \sim 1.5\times$SM and $4\ell \sim small$.

- For $\Lambda_\phi = 1$ TeV, $m_h = 125$ GeV, $m_\phi = 137$ GeV get rough description at $m_0/m_{Pl} = 0.6$ and $\xi = -0.05$

- For $\Lambda_\phi = 1.5$ TeV, can do better.

  Fig. 5 (next page) shows results for $m_h = 125$ GeV and $m_\phi = 137$ GeV.

  For $m_0/m_{Pl} = 0.25$ and $\xi \sim -0.1 \Rightarrow$

  125 GeV: $\gamma\gamma \sim 2\times$SM and $4\ell \sim 1.5\times$SM. signals

  137 GeV: $\gamma\gamma \sim 2\times$SM and 4ℓ very suppressed.

- For $\Lambda_\phi = 1$ TeV or 1.5 TeV, the reverse configuration of $m_h = 137$ GeV and $m_\phi = 125$ GeV is not good.

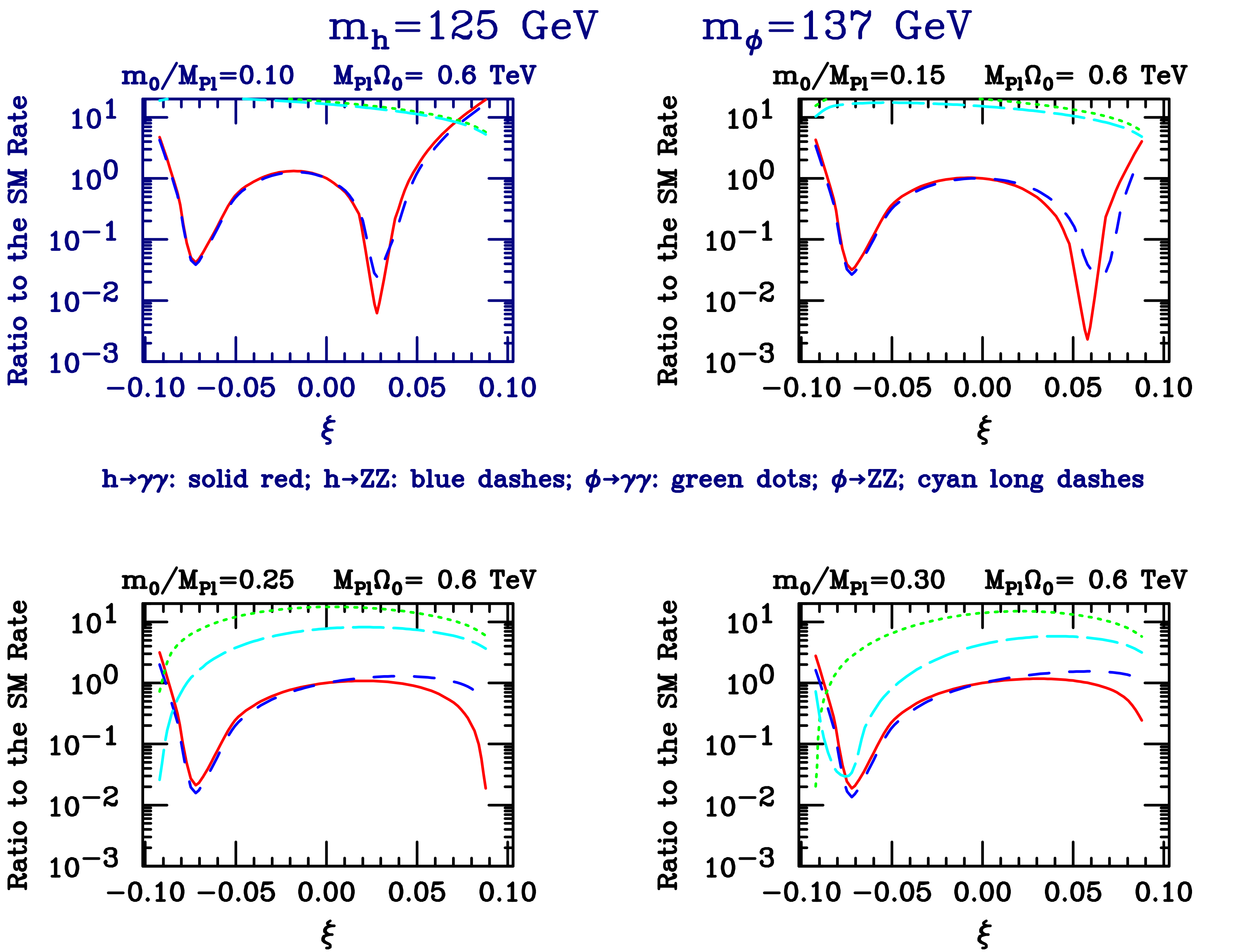


Figure 5: $\gamma\gamma$ and ZZ rates relative to SM vs ξ taking Λ_ϕ fixed at 1.5 TeV.

Signals at 125 GeV and 500 GeV

- For $\Lambda_\phi = 1.5$ TeV,

  With $m_h = 125$ GeV and $m_\phi = 500$ GeV there are m_0/m_{Pl} and ξ choices such that the predicted 125 GeV excesses in $\gamma\gamma$ and 4ℓ are at the level of $(1.5 - 2)\times$SM.

  However, for these parameter choices the 500 GeV signals for 4ℓ are at a level of $\sim 3\times$ SM and thus pretty much ruled out.

  For the reverse case of $m_h = 500$ GeV and $m_\phi = 125$ GeV there again are m_0/m_{Pl} and ξ choices that give excesses of $(1.5 - 2)\times$SM in both $\gamma\gamma$ and 4ℓ, but the 500 GeV excesses are far to large.

  Thus, for $\Lambda_\phi = 1.5$ TeV if one of either the radion or the higgs is heavy and one at 125 GeV, the heavy higgs must be beyond LHC reach to avoid conflict with data at large mass if reasonable consistency with the 125 GeV excesses is to be maintained.

- **For $\Lambda_\phi = 1$ TeV,**

  If $m_h = 125$ GeV and $m_\phi = 500$ GeV then excesses in 4ℓ and $\gamma\gamma$ at 125 GeV of order $2\times$SM are possible at large ξ, but the 500 GeV 4ℓ signal is far too big.

  In the reverse case of $m_h = 500$ GeV and $m_\phi = 125$ GeV, one can obtain $\gamma\gamma$ and 4ℓ signals at 125 GeV of order $2 \times SM$ and $0.8\times$SM with a 4ℓ excess at 500 GeV of order $2\times$SM.

  This not in disagreement with CMS observation in this mass region, but ATLAS has a deficit.

  One can, of course, choose to describe only the 125 GeV excesses by taking $m_h > 1$ TeV (which leaves the $m_\phi = 125$ GeV excess prediction unchanged) to avoid any possible conflict with the 500 GeV region data.

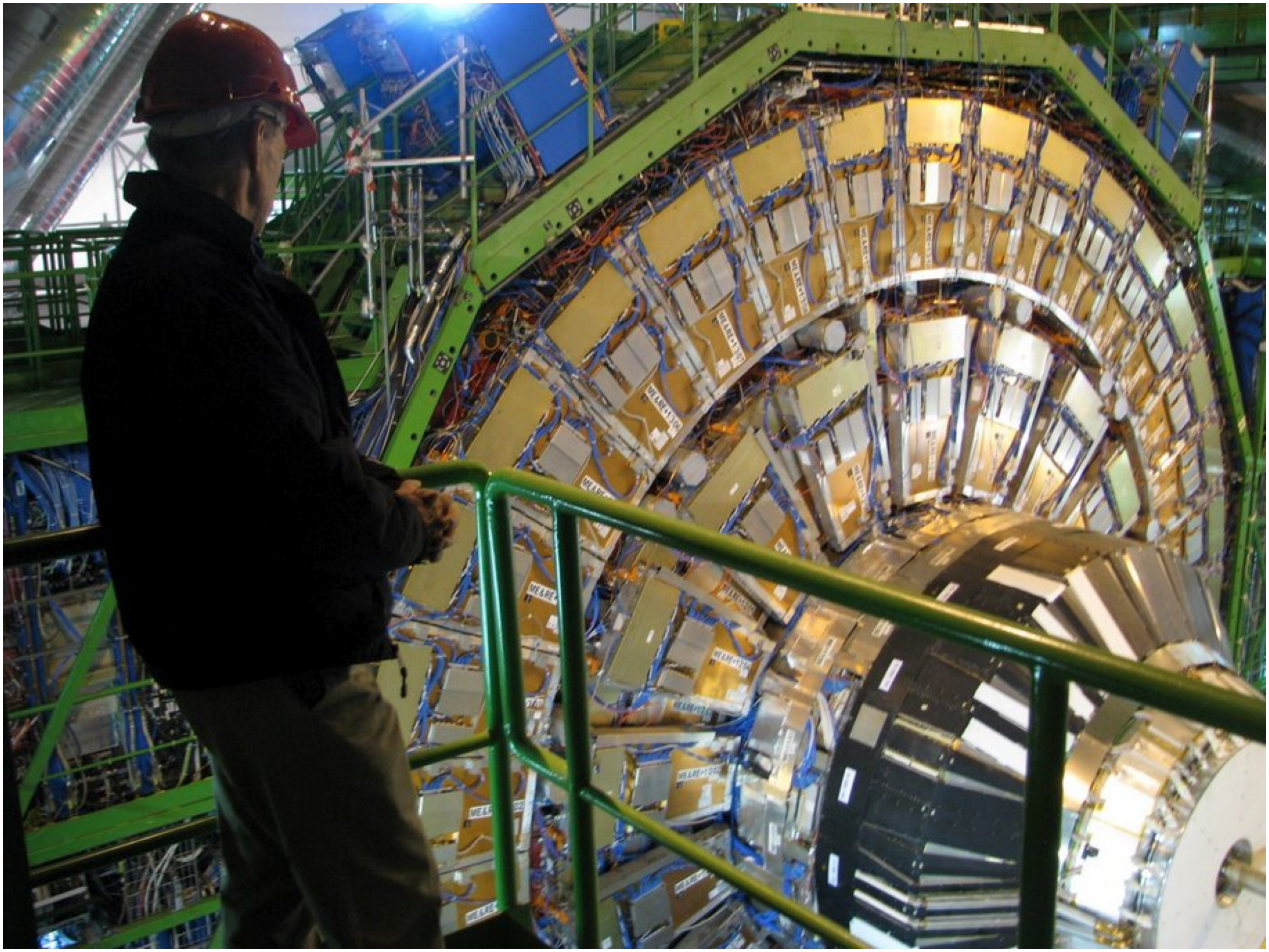
Conclusions

It seems likely that the Higgs responsible for EWSB is not buried

Perhaps, other Higgs-like objects are emerging.

But, must never assume we have un-buried all the Higgs.

Certainly, I will continue watching and waiting



References

[1] L. Randall and R. Sundrum, "A large mass hierarchy from a small extra dimension," Phys. Rev. Lett. 83 (1999) 3370 [arXiv:hep-ph/9905221];

[2] H. Davoudiasl, J. L. Hewett and T. G. Rizzo, Phys. Lett. B 473, 43 (2000) [hep-ph/9911262].

[3] A. Pomarol, Phys. Lett. B 486, 153 (2000) [hep-ph/9911294].

[4] T. Gherghetta, A. Pomarol, "Bulk fields and supersymmetry in a slice of AdS," Nucl. Phys. B586, 141-162 (2000). [hep-ph/0003129].

[5] H. Davoudiasl, J. L. Hewett, T. G. Rizzo, Phys. Rev. D63, 075004 (2001). [hep-ph/0006041].

[6] C. Csaki, J. Erlich and J. Terning, Phys. Rev. D 66, 064021 (2002) [hep-ph/0203034].

[7] J. L. Hewett, F. J. Petriello and T. G. Rizzo, JHEP 0209, 030 (2002) [hep-ph/0203091].

[8] K. Agashe, A. Delgado, M. J. May and R. Sundrum, JHEP 0308, 050 (2003) [hep-ph/0308036].

[9] K. Agashe, H. Davoudiasl, G. Perez and A. Soni, Phys. Rev. D 76, 036006 (2007) [hep-ph/0701186].

[10] D. Dominici, B. Grzadkowski, J. F. Gunion and M. Toharia, "The scalar sector of the Randall-Sundrum model," Nucl. Phys. B 671, 243 (2003) [arXiv:hep-ph/0206192]; "Higgs-boson interactions within the Randall-Sundrum model," Acta Phys. Polon. B 33, 2507 (2002) [arXiv:hep-ph/0206197].

[11] G. Cacciapaglia, C. Csaki, J. Galloway, G. Marandella, J. Terning and A. Weiler, JHEP 0804, 006 (2008) [arXiv:0709.1714 [hep-ph]].

[12] K. Agashe, A. Belyaev, T. Krupovnickas, G. Perez and J. Virzi, Phys. Rev. D 77, 015003 (2008) [hep-ph/0612015].

[13] G. Aad *et al.* [ATLAS Collaboration], arXiv:1112.2194 [hep-ex].

[14] S. Chatrchyan *et al.* [CMS Collaboration], arXiv:1112.0688 [hep-ex].

[15] S. Rappoccio [CMS Collaboration], arXiv:1110.1055 [hep-ex].

[16] The ATLAS Collaboration, " A Search for ttbar Resonances in the Dilepton Channel in 1.04/fb of pp Collisions at sqrt(s) = 7 TeV", ATLAS-CONF-2011-123.

[17] G. F. Giudice, R. Rattazzi and J. D. Wells, "Graviscalars from higher-dimensional metrics and curvature-Higgs mixing," Nucl. Phys. B 595, 250 (2001) [arXiv:hep-ph/0002178].

[18] J. L. Hewett and T. G. Rizzo, JHEP 0308, 028 (2003) [hep-ph/0202155].

[19] C. Csaki, J. Hubisz, S. J. Lee, "Radion phenomenology in realistic warped space models," Phys. Rev. D76, 125015 (2007). [arXiv:0705.3844 [hep-ph]].

[20] H. de Sandes, R. Rosenfeld, "Radion-Higgs mixing effects on bounds from LHC Higgs Searches," [arXiv:1111.2006 [hep-ph]].

[21] V. Barger, M. Ishida, "Randall-Sundrum Reality at the LHC," [arXiv:1110.6452 [hep-ph]].

[22] K. Cheung and T. -C. Yuan, arXiv:1112.4146 [hep-ph].

[23] V. Barger, M. Ishida and W. -Y. Keung, arXiv:1111.4473 [hep-ph].

[24] ATLAS Collaboration, Combination of Higgs Boson Searches with up to 4.9 fb^{-1} of pp Collisions Data Taken at a center-of-mass energy of 7 TeV with the ATLAS Experiment at the LHC, ATLAS-CONF-2011-163.

[25] CMS Collaboration, Combination of SM Higgs Searches, CMS-PAS-HIG-11-032.

[26] ATLAS Collaboration, Search for the Standard Model Higgs boson in the decay channel $H \to ZZ^{(*)} \to 4\ell$ at $\sqrt{s} = 7$ TeV.

[27] CMS Collaboration, Search for a Higgs boson produced in the decay channel 4l, CMS-PAS-HIG-11-025.